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Temporal fluctuations in soil water repellency following wildfire in chaparral steeplands, southern California

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Abstract. Soil water repellency is particularly common in unburned chaparral, and its degree and duration can be influenced by seasonal weather conditions. Water repellency tends to increase in dry soils, while it decreases or vanishes following precipitation or extended periods of soil moisture. The 15 426 ha Williams Fire provided an opportunity to investigate post-fire fluctuations in water repellency over a 1-year period. Soil water repellency was measured at the surface, and at 2-cm and 4-cm depths along six east–west-positioned transects located within the chaparral-dominated San Dimas Experimental Forest. During the winter and spring, seasonal variation in the degree of surface water repellency appeared to be inversely proportional to antecedent rainfall and soil moisture conditions. Precipitation through December reduced the proportion of surface 'moderate or higher repellency' from 49 to 4% as soil wetness increased to 12%. Throughout the summer, soil wetness remained below 2%; however, surface soils remained 'wettable', with the proportion of surface 'moderate or higher repellency' never returning to the early post-fire amount of 47%. Interestingly, at the 4-cm depth, the proportion of 'moderate or higher repellency' remained at levels >25% throughout the summer dry season.

Introduction

In southern California, soil water repellency is particularly common in unburned woodland chaparral communities, due in part to the dry Mediterranean climate, coarse-textured soils, and the high resin content of chaparral plants and chaparral litter material (Holzhey 1969; DeBano 1981). Water-repellent substances are naturally occurring and are derived from organic compounds of most living or decomposing plant species, and from microorganisms in grasslands, shrublands and forests. The magnitude and persistence of repellency may differ depending on the chemical nature and amounts of resins, waxes or aromatic oils contributed by different species of chaparral commonly associated with water repellency (Hubbert *et al.* in press). Fungal growth is known to produce water repellency (Bond 1964; Fogel and Hunt 1979), and where growth is present, soils can remain highly repellent even under moist conditions (Hubbert *et al.* in press).

During intervals between fires, water-repellent compounds may accumulate at the soil surface and be transferred into the soil as leachate from litter material (DeBano 1981) or by leaf drip, decomposition of organic matter, root and mycorrhizal secretions, repellent microbial biomass and exudates, and mechanical removal of waxy leaf particles of the chaparral plant (Neinhuis and Barthlott 1997; Hallett and Young 1999). It has been suggested that light to moderate burning of chaparral plant and litter material can induce repellency in previously wettable soils by releasing a flush of water-repellent substances that are deposited onto and into the soil (DeBano *et al*. 1976). Further post-fire layering patterns of repellency include: (1) enhancement of previous repellency (Scholl 1975); (2) destruction of previous surface repellency and induction of a subsurface repellency layer (Scott and Van Wyk 1990); and (3) no apparent change in soils that were already extremely repellent (Doerr *et al*. 1996). Water-repellent substances present in the soil are volatized and translocated downward into the soil along a temperature gradient, recondensing at cooler soil temperatures (DeBano *et al.* 1970). Water repellency is generally intensified at temperatures of 175–200°C, but can be destroyed above 270–300°C (Savage 1974).

Under natural conditions, it is thought that water-repellent soils typically alternate seasonally or over shorter intervals between repellent and non-repellent states in response to seasonal weather conditions, specifically rainfall and temperature patterns (Dekker *et al*. 1998; Doerr and Thomas 2000; Shakesby *et al*. 2000). There is, however, relatively limited evidence of the mechanisms by which hydrophilic conditions develop in wet weather, or hydrophobic conditions in periods of dry weather, and, in particular, limited understanding of the time taken and conditions required for this to occur (Shakesby *et al*. 2000; Leighton-Boyce *et al*. 2003).

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In most cases, soil water repellency tends to increase in dry soils, while it decreases or vanishes following precipitation or extended periods of soil wetness (Dyrness 1976; Crockford *et al*. 1991; Ritsema and Dekker 1994). This may not always be the case, as Doerr and Thomas (2000) reported repellency in relatively moist soils at up to 28% soil wetness.

Temporal fluctuations in soil water repellency following wildfire remain largely unexplained, as does the erosional impact that repellency plays on a catchment scale (Doerr *et al*. 2000). The aim of this study was to investigate in detail the post-fire fluctuations in soil water repellency within a chaparral landscape, and to assess the proportion of repellency in relation to antecedent precipitation and soil moisture. Repellency and soil moisture were assessed on 17 occasions over a period of 12 months (November 2002 to October 2003) at eight points spaced unevenly along six 50-m transects. *In situ* repellency was assessed at the surface and at 2-cm and 4-cm depths using the water drop penetration time (WDPT) method. This study aims to add to the understanding of post-fire temporal fluctuations of soil water repellency and to facilitate successful management of its hydro-geomorphic effects.

Methods

Site description

The ~3 ha study watershed (34°12′45″N, 117°45′30″W) is located within the San Dimas Experimental Forest (SDEF) in the foothills of the San Gabriel Mountains of southern California, ~45 km north-east of Los Angeles. The climate is Mediterranean, with hot, dry summers and cool, wet winters. Temperatures range from −8°C to 40°C during the year (Crawford 1962). Mean annual precipitation is 678 mm (Dunn *et al*. 1988).

From 22 September to 2 October 2002, the Williams Fire burned 13 747 ha of National Forest Service land including >90% of the 6947 ha of the SDEF. The USDA Forest Service Burned Area Emergency Rehabilitation (BAER) team reported low burn severity of 3322 ha, moderate burn severity of 6015 ha, high burn severity of 1982 ha and 2428 ha unclassified. Fire severity was based on the following fire intensity site indicators: (1) depth and color of ash; (2) size and amount of live fuels consumed; (3) litter consumption; (4) plant root crowns; and (5) soil crusting (USDA Forest Service 1995). Of the 13 747 ha burned, a total of 11 347 ha was considered water repellent (Napper 2002). Burned areas of the SDEF were labeled as moderate to high burn severity and were mapped as water repellent. Evaluation of the spatial extent of water repellency in soils was based on mapped fire intensity and fire residence time (Napper 2002). The repellency estimates were verified by random sampling of the burned areas using the WDPT method (USDA Forest Service 1995).

The Williams Fire occurred toward the end of the summer dry season, at a time when both fuel and moisture were very low. Because there was no wind, the fire was fuel driven with the rate of fire spread being relatively slow. The rate of spread was noticeably faster upslope, and slower when backing down slope. Low burn severity was more evident where fuel loads were smaller and the fire burned upslope. The fire consumed most of the litter layer, leaving only a thin layer of ash. One week following the fire, the area experienced 2 days of high winds (foehn – known locally as Santa Ana winds). The winds disturbed the surface and much of the ash layer was redistributed, either carried offsite, or redeposited in the watershed.

Fifteen months before the wildfire (May 2001), pre-fire water repellency data was collected in a watershed adjacent to the present study site using the WDPT method and similar experimental design. The sites were considered comparable owing to similar vegetation type, pre-fire biomass, geomorphology, soil types, aspect, slope and elevation. The mean soil moisture at the time of repellency sampling, however, was measured at 13% wetness by volume for the 0–5-cm depth. It is probable that 0–2-cm depth moisture content was below 13% wetness by volume. This particular watershed was not resampled because it remained largely unburned following the Williams Fire.

Soils and geology

The topography of the SDEF is rugged with precipitous canyons and steep slopes throughout (Ryan 1991). Much of the rock is Pre-Cambrian to Mesozoic strongly banded and foliated gneisses and schists, mixed with a large percentage of igneous dike rocks, mostly diorites and granodiorites along with pegmatite and dacite (Storey 1948). Bedrock in the area has been subjected to intense heat and pressure resulting in a high degree of alteration, faulting, folding and fracturing. As a result, the rocks are poorly consolidated and very unstable (Sinclair 1953). Extensive fracturing has allowed deep weathering of the rock, providing considerable storage capacity for water. Soils were classified in terms of the USDA soil classification system as coarse-loamy, mixed, thermic Typic Xerorthent (Hubbert *et al.* in press). Soils are shallow (mean depth 25 cm), low in organic matter and coarse-textured with rock fragments throughout, are situated on very steep slopes (Jones and Graham 1993), and overlie weathered bedrock that extends on average another 70 cm. Over 90% of the watershed area has slopes exceeding 55%. Soil material on these slopes moves too frequently to allow strong development of soil horizons.

Vegetation

The natural vegetation is chaparral, characterized by sclerophyllous leaves, 1–4 m plant height and dense canopies. Common species include chamise (*Adenostoma fasciculatum* Hook and Arn.), hoaryleaf ceanothus (*Ceanothus crassifolius* Torr.), sugar bush (*Rhus ovata* S. Winston), Eastwood manzanita (*Arctostaphylos glandulosa* Eastw.), scrub oak (*Quercus berberidifolia* Liebm.), black sage (*Salvia* *melliflora* E. Greene) and wild buckwheat (*Eriogonum fasciculatum* Benth.). The stand age of the chaparral was 42 years, with the watershed last burning in 1960 during the Johnstone Fire that consumed 88% of the SDEF.

Field and laboratory measurements

Four points were randomly selected on the west ridge of the watershed. From two of these points, three 50-m transects were positioned in an east–west direction across the watershed in a chevron pattern for a sum total of six transects. Sampling sites were unevenly spaced at 0, 1, 2, 4, 8, 16, 32 and 50 m along the transect lines. The uneven spacing allowed for representative sampling of the crest, upper, middle and lower backslopes, and toe and foot of the watershed slope morphology. At each sampling point, soil water repellency was determined by noting the WDPT (Krammes and DeBano 1965; Letey 1969). Ash and unburned and partially burned litter material were carefully removed to expose the soil mineral surface. Sampling was done at approximately 1–4-week intervals for 12 months following the wildfire. Twenty water drops were applied using a squeeze bottle to the mineral soil surface within a 15 × 15 cm area. Another 20 measurements were taken at the 2-cm depth and 10 measurements at the 4-cm depth. The WDPT was determined when the droplet changed from convex to flat and infiltrated the soil. Existing soil water repellency indices (DeBano 1981; Dekker and Ritsema 2000) were modified to give the following classification scheme: 0–5 s, 'wettable'; 5–30 s, 'slight'; and >30 s, 'moderate or higher repellency'. The WDPT of each of the 20 drops were counted individually and the percentage was calculated from the mean of the total measurements.

Precipitation, relative humidity (RH) and air temperature data were obtained from the RAWS Tanbark Station (Western Regional Climate Center 2005) located within the SDEF (Tables 1, 2). To determine soil moisture, samples were taken at 0–2-cm and 2–4-cm depths, placed in sealed sample tins, and transported in a cooler to the laboratory. At each point along the six transects, soil moisture samples were taken concurrently with WDPT at both 0–2-cm and 2–4-cm depths. At each depth, samples were taken in triplicate and combined. Soil wetness measurements were made gravimetrically after oven drying (Gardner 1986).

Results and discussion

Pre- and post-fire surface, 2-cm and 4-cm repellency

The proportion of 'moderate or higher repellency' at the surface, 2-cm and 4-cm depths was greater on the first post-fire sampling occasion than was recorded in the pre-fire sampling in the unburned watershed. In the unburned 40-year-old woodland chaparral stand, the proportions of surface soil water repellency measurements were reported as 41% 'wettable', 22% 'slight' and 37% 'moderate or higher repellency'; at the 2-cm depth as 53% 'wettable', 14% 'slight'

Table 1. Maximum, minimum and mean air temperatures and relative humidity for dates sampled for water drop penetration time

Variable	7 Nov. 2002	20 Nov. 2002	8 Jan. 2003	6 Feb. 2003	3 Mar. 2003	27 Mar. 2003	16 Apr. 2003	2 May 2003	15 May 2003	29 May 2003	18 Jun. 2003	16 Jul. 2003	5 Aug. 2003	26 Aug. 2003	3 Sep. 2003	9 Oct. 2003
Air temperature (°C)																
Max.	8.9	28.9	17.8	15.0	11.1	20.0	16.7	15.6	21.1	31.7	25.6	39.4	31.1	32.2	35.0	32.2
Min.	18.9	19.4	8.9	5.0	5.0	10.6	3.9	6.7	5.6	12.8	12.2	25.6	17.8	21.1	22.2	13.9
Mean	13.5	23.2	12.7	9.0	8.1	15.4	9.5	10.4	13.9	23.2	18.7	32.2	24.0	25.9	28.0	23.8
Relative humidity (%)																
Max.	67	22	93	44	89	68	75	95	97	97	96	37	40	43	52	95
Min.	11	12	89	10	30	17	30	34	51	20	44	10	12	19	27	13
Mean	27	17	62	22	56	40	58	69	71	52	69	21	24	33	39	40

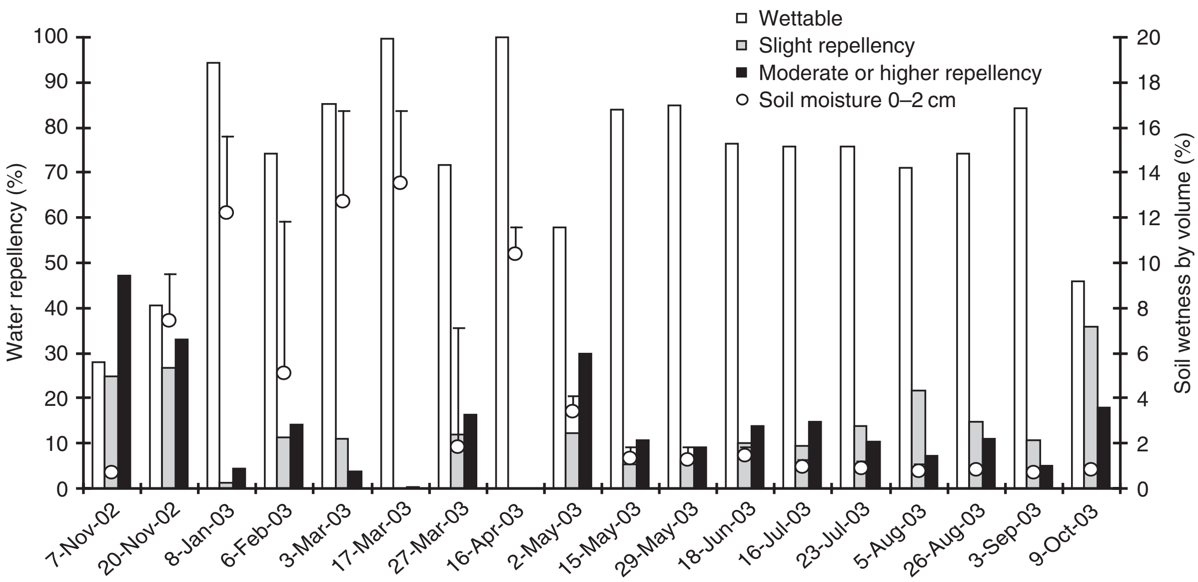

Fig. 1. Temporal fluctuation of 'wettable', 'slight' and 'moderate or higher' soil water repellency at the soil surface in relation to % soil wetness by volume during a 12-month period following wildfire. Error bars for soil wetness represent one standard deviation of the mean.

and 33% 'moderate or higher repellency'; and at the 4-cm depth as 90% 'wettable', 6% 'slight' and 4% 'moderate or higher repellency' (Hubbert *et al.* in press). Thirty-five days following the wildfire, the proportion of surface soil water repellency measurements was 28% 'wettable', 25% 'slight repellency' and 47% 'moderate or higher repellency' (Fig. 1). Because soil moisture conditions were not similar at the time of pre- and post-fire sampling, the increases in the proportion of post-fire repellency may be higher than if the pre-fire soils had been drier. The increase in the extent or spatial frequency of repellency following fire may be a result of movement on and into the soil of water-repellent substances released from burning plant and litter material, a mechanism reported by DeBano *et al.* (1970). Additionally, repellent substances already present in the soil matrix may have been altered such that they induced repellency (Savage *et al*. 1969; Valat *et al*. 1991; Franco *et al*. 1995). It has been suggested by Teramura (1980) that chaparral vegetation and litter release hydrophobic compounds to the soil during the time period between fires by decomposition and leaching. At the 2-cm depth, the present results show the proportion of 'moderate or higher repellency' increasing from 33 to 56% and at the 4-cm depth from 4 to 36.2%. This pattern fits the translocation model of DeBano *et al*. (1970).

A large precipitation event of 126 mm (Tables 1, 2) lasting from 8 to 10 November immediately followed the November repellency sampling. Only minor sheet erosion was observed on the steep slopes after this storm, and there was no sediment collected at the catchment dam located at the mouth of the watershed. In this low-intensity storm event, it appeared that water repellency had no influence on erosion, even though the proportion of surface 'moderate or higher repellency' was 47%. It is believed that most of the precipitation infiltrated into the soil, as the soils were dry and storage capacity of the soil and weathered bedrock was sufficient. This suggests that spatial variability of water repellency across the landscape was such that infiltration was not limited (Hubbert *et al.* in press). From 16 to 20 December, a second large but low-intensity storm event of 79 mm occurred. After this event, rilling was observed on the steep slopes and the catchment dam was filled with sediment. In this case, it appears that antecedent moisture conditions made full the soil and bedrock storage capacity, resulting in the commencement of saturated overland flow during the additional rain. With the removal of vegetation by the wildfire, the lack of transpiration between the two storm events contributed greatly to this effect.

Seasonal fluctuations in water repellency

From November 2002 through May 2003, seasonal variation in the degree of water repellency at the soil surface appeared to be inversely proportional to antecedent rainfall and soil wetness conditions. Following the 3-day rain event (8–10 November 2002) of 126 mm (Tables 1, 2), the proportion of surface 'moderate or higher repellency' measurements decreased from 49 to 35% as soil moisture increased from 0.7 to 7.4% (Fig. 1). Regular rain events through December (amounting to 93 mm) (Tables 1, 2) increased soil moisture to 12.2%, resulting in a reduction of 'moderate or higher repellency' from 35 to 4%, and increasing the proportion of 'wettable' from 25 to 91% (Fig. 1). Similar patterns have been reported previously by Leighton-Boyce *et al*. (2003) under *Eucalyptus globulus* plantations in north-central Portugal, and by Huffman *et al*. (2001) in ponderosa and lodgepole pine in the Colorado Front Range. During

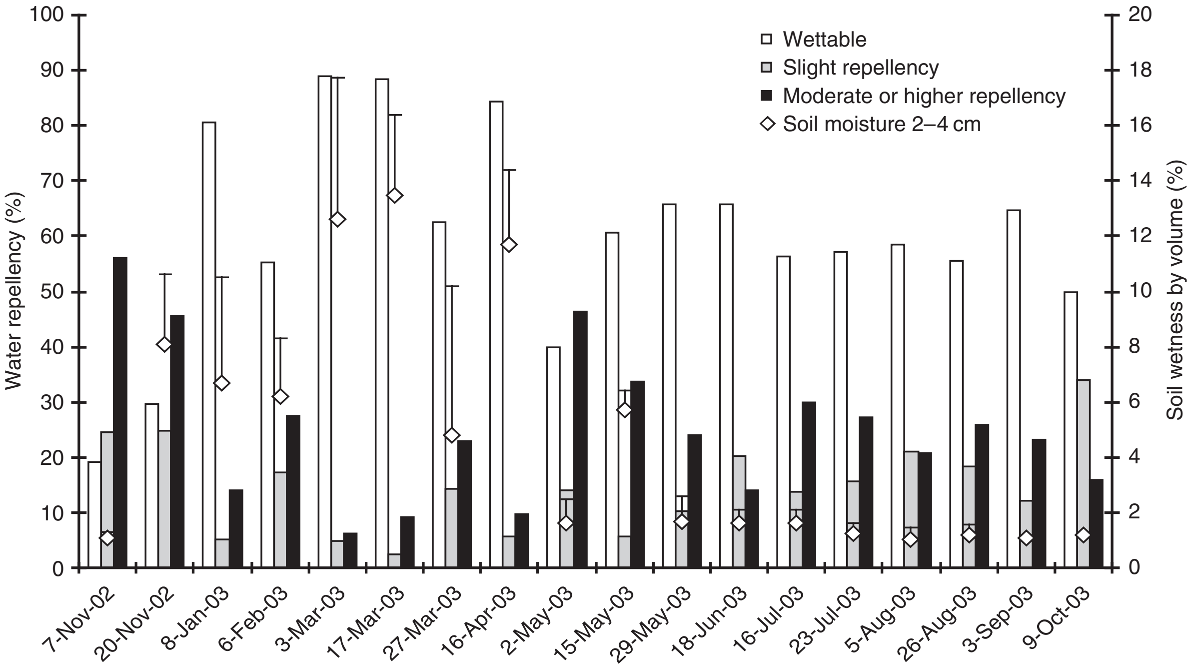

Fig. 2. Temporal fluctuation of 'wettable', 'slight' and 'moderate or higher' soil water repellency at the 2-cm depth in relation to % soil wetness by volume during a 12-month period following wildfire. Error bars for soil wetness represent one standard deviation of the mean.

the winter and spring rain events, the proportion of surface 'wettable' repellency remained above 70%, only dropping to 58% on 2 May (Fig. 1). On two occasions (17 March and 16 April), the proportion of surface 'moderate or higher repellency' measurements dropped to near 0% when the sampling time immediately followed a rain event (Tables 1, 2) and soil moisture was above 10% wetness by volume (Fig. 1). During the summer dry season, the proportion of surface 'moderate or higher repellency' measurements returned to less than half the November 2002 pre-rain amount of 47% at the soil surface (Fig. 1).

At the 2-cm and 4-cm depths, the proportion of 'moderate or higher repellency' also tended to decrease during the winter months as percentage soil moisture increased, but the decrease was not as pronounced as for the surface soil (Fig. 2). On both 27 March and 2 May, at the surface, 2-cm and 4-cm depths, large increases were observed in the proportion of 'moderate or higher repellency' following periods of drying after rain events (Figs 2, 3, Table 2). After the 15–17 March rain event of 108 mm, soil wetness dropped from 13.5 to 4.7% during a 10-day drying period, and after the 13–15 April rain event, soil wetness dropped from 11.7 to 1.6% during a 16-day drying period (Fig. 2, Tables 1, 2). This may be an additional result of increased evapotranspiration attributed to the flush of new spring growth of fine roots and associated mycorrhizal hyphae. The proportion of 'moderate or higher repellency' measurements at the 2-cm depth remained above 20% through the dry period (Tables 1, 2), except for 18 June (14%), with soil wetness remaining below 2% during this same period (Fig. 3). On 7 and 20 November 2002, the proportion of 'moderate or higher repellency' at the 2-cm depth was >15% higher than was measured at the 4-cm depth (Figs 2, 3). After winter precipitation and periods of soil wetness above 10%, this trend was reversed, and the proportion of 'moderate or higher repellency' at the 4-cm depth remained higher than that at the 2-cm depth through the summer dry season (Figs 2, 3). It appears that one cause of this effect may be soluble water-repellent substances being leached downward from the 2-cm depth to the 4-cm depth during the wet periods.

It is still unclear above what critical soil moisture content water repellency disappears (i.e. critical soil moisture zone theory) and soils remain hydrophilic (Dekker and Ritsema 2000; Doerr and Thomas 2000; Dekker *et al*. 2001). From 7 to 20 November 2002, the results showed only a gradual decrease in surface 'moderate or higher repellency' following precipitation of 126 mm from 8 to 10 November (Tables 1, 2). Some drying at the soil surface had occurred since the rain event, however, and soil wetness was measured at 7% on 20 November 2002 (Fig. 1). However, with regular rain events in December, the soil surface proportion of 'moderate or higher repellency' dropped to 4% on 8 January as soil wetness increased to above 12% (Fig. 1). The month of January 2003 was unusually hot and dry, and by 6 February, soil wetness at the 0–2-cm depth had dropped to 5% (Fig. 1). A small return only was witnessed in soil surface proportion of 'moderate or higher repellency' at this lower water content (Fig. 1). This pattern supports the critical soil moisture zone

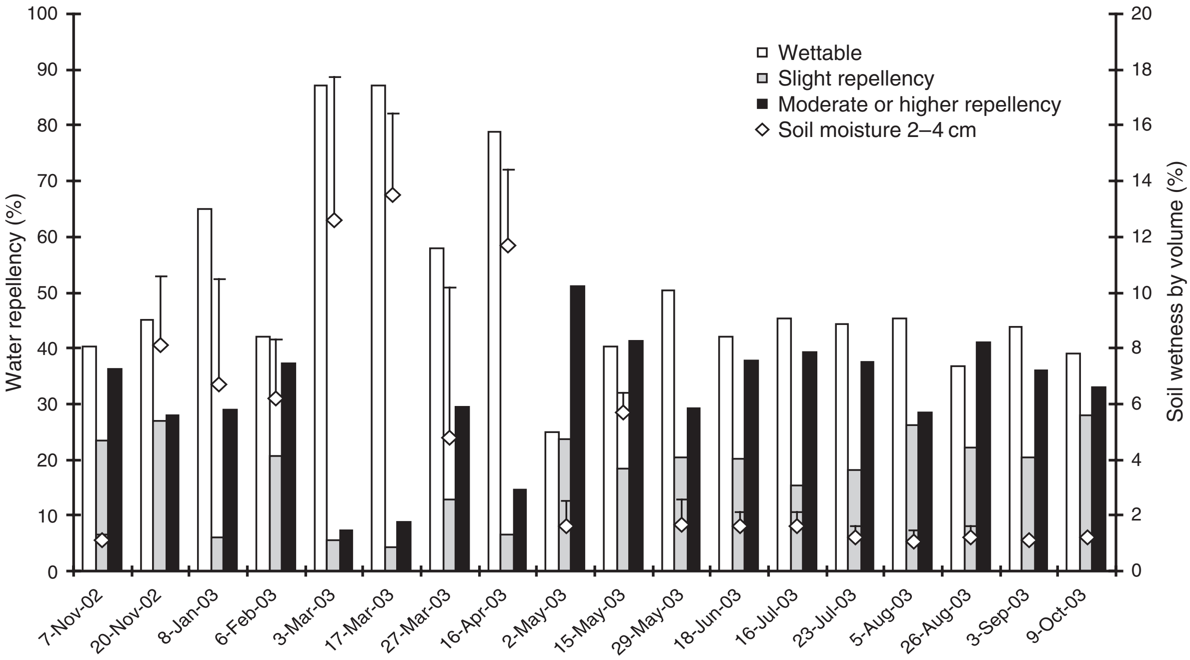

Fig. 3. Temporal fluctuation of 'wettable', 'slight' and 'moderate or higher' soil water repellency at the 4-cm depth in relation to % soil wetness by volume during a 12-month period following wildfire. Error bars for soil wetness represent one standard deviation of the mean.

theory introduced by Dekker *et al.* (2001), which makes the statement, 'critical soil water content appears not to be a sharp threshold above which a soil is water repellent, but rather a transitional stage'. At the 2-cm and 4-cm depths, however, a much greater increase in 'moderate or higher repellency' was observed (Fig. 1), even though percentage soil wetness was higher (Fig. 1). At the 4-cm depth, the proportion of 'moderate or higher repellency' persisted at levels >25% from 2 May to 9 October 2003 (Fig. 3). This may be due to the highly spatial nature of soil wetness at different slope, aspect and landscape positions. This can be seen in the large variation in soil wetness measurements when soil water content was high, as indicated by the large error bars in Fig. 1. There was little variation in soil wetness error when soils were dry.

Figures 1–3 suggest that a period of wetting (in this case from November 2002 to March 2003), which included several regularly occurring rain events (Tables 1, 2), is needed to reduce water repellency. In soils of mixed chaparral shrublands, it further appears that soil wetness must be maintained above 10% for soils to remain wettable (Figs 1–3). Below 2% soil wetness, repellency returned at the 2-cm and 4-cm depths and was maintained as the soils dried (Figs 1–3). Robichaud (1996) noted a decrease in water repellency as the soil profile became moist, and no water repellency after the third rain event. In a study conducted by Crockford *et al.* (1991), a long consistent wet period (several weeks) was required for water repellency to break down and continuous cool wet conditions were needed for it to remain broken down. On very steep slopes, lateral wetting from contiguous macropores and cracks may be important in helping to break down severe water repellency. As hydrophilic soils below water-repellent layers saturate, capillary rise can act to wet and break down the upper repellent layers (Hendrickx *et al.* 1993).

Little increase was observed in the surface soil proportion of 'moderate or higher water repellency' throughout the summer dry season (29 May to 9 October), although soil wetness was <2% (Fig. 1) and temperatures of >70°C were observed at the soil surface. This was contrary to expectation based on studies conducted by Crockford *et al.* (1991), Dekker *et al.* (1998) and Shakesby *et al.* (2000). Crockford *et al.* (1991) reported that hot dry periods allow soil water repellency to become re-established, and Shakesby *et al.* (2000) reported that soils were highly water repellent after long periods of drying. Dekker *et al.* (1998) showed that soil drying at 25 and 45°C induced slight repellency (5–60 s), and further drying at 65°C induced slight to extreme repellency (60–3600 s). Fires greatly alter soil temperatures by removing shade, blackening the surface and removing the insulating litter layer, resulting in greater daily and seasonal temperature extremes. It has been suggested by Doerr and Thomas (2000) that repellency is not always re-established when soils become dry after wetting. The authors also suggested that re-establishment of repellency may require a fresh input of water-repellent substances during wetting. In regard to the present study, there was little or no input of new water-repellent substances to the soil surface during periods of wetting, because the wildfire had consumed the vegetation and the chaparral species were just beginning to resprout. The return of repellency to the

Table 2. Precipitation events recorded for water drop penetration time
Precipitation amounts calculated for duration of each storm event

Date	8–10 Nov. 2002	30 Nov. to 1 Dec. 2002	16–20 Dec. 2002	29–30 Dec. 2002	8–9 Jan. 2003	11–14 Feb. 2003	25 Feb. to 5 Mar. 2003	15–17 Mar. 2003	2–3 Apr. 2003	13–15 Apr. 2003	20–23 Apr. 2003	2–8 May 2003	9 May to 9 Oct. 2003	Total
Precipitation (mm)	126.1	7.8	78.8	7.4	5.6	121.0	50.0	108.2	3.8	60.7	13.2	47.0	0	629.6

soil surface over time likely depends on the post-fire recovery and increase of the chaparral biomass, the known source of water-repellent compounds.

Further explanations for the lower than expected values for surface 'moderate or higher repellency' include: (1) a lack of new chaparral litter and plant cover that would provide an influx of new hydrophobic compounds; (2) movement and disturbance of the steep surface soils by gravity (dry ravel) and strong winds; (3) micro-, meso- and macro-bioturbation (visible ant activity) (Bond 1964); (4) leaching of hydrophobic compounds from the surface to the 2-cm and 4-cm depths during winter rain events; and (5) high variability in soil water content at different depths (Dekker *et al*. 2001). In addition, large diurnal variation in air temperature and RH may play an unknown role concerning surface repellency (Table 1). An increase in water repellency with short exposure to high RH has been reported previously by Doerr *et al.* (2002). The watershed is also influenced by coastal marine layers (cool and moist air layers that increase with thickness to a few thousand feet inland toward the mountains) that commonly occur at any time through the spring and summer months. During these periods, moisture will condense and drip from surface plants, adding moisture to the soil surface. Although leaf drip has a minimal effect on soil moisture content, it may add more water-repellent substances to the soil surface. The low frequency of surface water repellency through the summer and fall as compared to repellency immediately following the fire further suggests that the initial first-year grass and herbaceous fire followers do not contribute water-repellent compounds to the soil surface.

Dry ravel, ash deposition, redistribution of soil and ash material, and fungal mats

Dry ravel is the unconsolidated flow of dry soil particles under the influence of gravity (Anderson *et al*. 1959; Rice 1974). Where the slopes exceed the angle of repose for the soil (the maximum angle at which unconsolidated material generally remains stable, slopes ~55–60%), any disturbance, even wind, can initiate this dry erosion process. When wildfire consumes the plant and litter cover, soils in chaparral shrublands become vulnerable to increased surface erosion. During and following wildfire, superficial rock fragments and fine earth materials, intermixed within the litter layers and trapped behind standing biomass, are liberated and move downslope by gravity (Krammes 1960). This constant movement of material downslope may contribute to the low proportion of 'moderate or higher repellency' observed in the surface soil through the summer dry period. In parts of southern California, dry ravel movement accounts for over half of all hillslope erosion, independently of fire (Anderson *et al*. 1959; Krammes 1969; Rice 1974). In a previous unpublished study, a substantial amount of material restrained on the hillslopes that is available for release upon removal of the standing plants and litter layers was determined by estimation.

Total potential dry ravel for the adjacent watershed (site of pre-fire repellency measurement) was 46 380 kg ha^{-1} for >2-mm material. Potential contributions of dry ravel for individual species coverage were 5940 kg ha^{-1} for scrub oak, 22 100 kg ha^{-1} for ceanothus, 11 160 kg ha^{-1} for sugar bush, 6730 kg ha^{-1} for chamise and 450 kg ha^{-1} for manzanita (K. R. Hubbert, unpublished data).

Strong winds redistributed and mixed ash and the loose surface mineral soil across the watershed. In some areas, accumulations of ash 5–10-cm thick were witnessed. As a result of movement of dry ravel material down the steep slopes, ash accumulations became buried beneath the soil surface. In most cases, the ash was buried to 1–4-cm depths, but in some areas ash was observed buried to 10 cm. Ash is very wettable, and in locations where it became buried, there was little or no water repellency. Lateral movement of water was also observed through these buried ash layers. On steep slopes, movement of water through these ash lenses could promote the breakdown of adjacent water-repellent layers.

In some cases, areas of 'moderate or higher repellency' were associated with remnant fungal mat pieces. The fungal mat pieces were located on top and interspersed within the loose surface soil mineral horizon (0–2 cm depth). The fungal mat pieces exhibited 'moderate or higher repellency' both pre- and post-fire and under both wet and dry soil conditions. Even though less than 10% of the watershed contained fungal mat material (ocular estimate pre-fire), these areas always exhibited 'moderate or higher repellency' even after being heated and broken up during the fire. Several authors have associated fungal mycelium with repellency, for example Richardson and Hole (1978), Reeder and Juergensen (1979) and Unestam (1991). Unestam (1991) reported that the water-repellent nature of fungal mycelia makes the surrounding soil water repellent. The wildfire resulted in the drying and weakening of the fungal mat structure, allowing it to break apart and move with the unstable soils. Consequently, post-fire fungal mat remnants were scattered at the surface and sometimes buried to the 2-cm and 4-cm depths. It has been noted by Savage *et al*. (1969) that any form of heating of fungal material will contribute to increases in water repellency.

Conclusions

Two weeks following the Williams Fire of moderate to high severity in the chaparral-dominated San Dimas Experimental Forest, the proportion of 'moderate or higher repellency' surface soils increased from 37 to 47%. During the winter and spring, seasonal variation in the degree of water repellency at the soil surface, 2-cm and 4-cm depths appeared to be inversely proportional to antecedent rainfall and soil moisture conditions. Regular rain events through December reduced the proportion of surface 'moderate or higher repellency' from 49 to 4% as soil wetness increased from 2 to 12%. Even though soil wetness remained below 2% throughout the summer and fall dry season, surface soils remained mostly 'wettable', with the proportion of surface 'moderate or higher repellency' never returning to the 7 November 2002 amount of 47%. The proportion of 'moderate or higher repellency' was, however, more pronounced at the 4-cm depth, remaining at levels above 25% throughout the following summer and fall dry season. Explanations for the low proportion of 'moderate or higher repellency' at the soil surface when soil wetness was <2% include: (1) dry ravel; (2) lack of new water-repellent compounds; (3) lateral movement of water through buried ash layers; (4) high temperatures at the soil surface; (5) wind erosion; (6) bioturbation; and (7) leaching of water-repellent compounds to lower depths. Following a period of rain events and soil wetting, it appears that soil wetness must be maintained above 10% before repellency is reduced or disappears. At the 2-cm and 4-cm depths, the results of the present study showed repellency returning at soil wetness below 2%.

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